1983

NDE Curricula Needs as Driven by Recent Technological Advances

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NDE CURRICULA NEEDS AS DRIVEN BY RECENT TECHNOLOGICAL ADVANCES

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During the last decade, major changes have been occurring in the NDE industry. Driven by advances in structural design, maintenance, and life extension practices, a new emphasis on the quantitative interpretation of nondestructive measurements has emerged (1-3). It is no longer practical to overdesign a system to accommodate the wide range of flaw sizes that might be accepted by a qualitative inspection. Instead, the cost, safety, and performance requirements of many major systems can only be attained by maximizing (and specifying) the reliability of flaw detection, by making quantitative estimates of the sizes of the detected flaws, and by measuring material properties and environmental conditions which influence the rate of flaw growth and the load at which catastrophic failure is expected to occur.

The state of the art has not proved adequate to meet these more stringent requirements. Both detection errors leading to false accepts and sizing errors leading to false rejects have been found to occur more frequently than system tolerances allow. The causes are twofold. First, the present techniques have not been optimized based on a full understanding of the physical principles involved. Second, a number of human factors have been identified which lead to poor operator performance.

In response to this need, several major R&D programs have been established which address the physical aspects of the problem. Among these are coordinated programs supported by the AF/Navy/DARPA and by EPRI, individual programs of DOE, DOD, NASA, NSF, NBS, NRC, DOT, AGA and other agencies, programs sponsored by private corporations and major efforts in other nations. The primary emphasis has been in the development of ultrasonic and eddy current techniques, with considerable attention to other established and emerging technologies as well.

Projecting into the future, it appears likely that the solution of the physical problems will be increasingly fruitful. However, the resulting more sophisticated techniques will tend to aggravate today's operator problem. The availability of knowledgeable personnel, both for the selection, design and deployment of automated systems and for the implementation of custom inspections, will be a limiting factor. Hence, it is essential that the education of these personnel be started today so that they will be ready when needed.

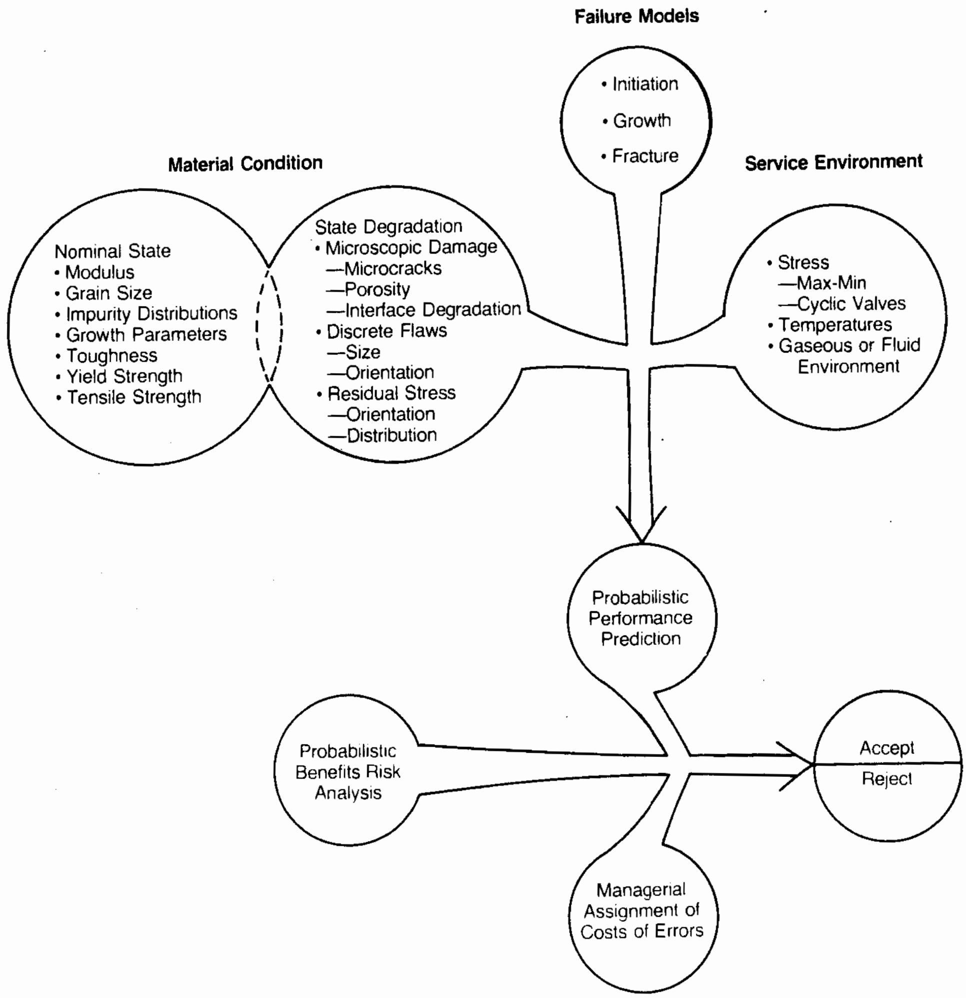


Fig. 1. Interdisciplinary procedures for establishing accept-reject criteria.

Figure 1 illustrates the interdisciplinary nature of the problem. The operator must understand the physical principles and signal processing procedures of the available measurement techniques so that those elements of the material condition applicable to the integrity of the structure under consideration can be sensed as accurately as possible. This information, along with knowledge of the failure mechanisms of the material and the loads and environments in which it will serve must then be combined in an appropriate statistical framework so that the optimum accept/reject decision can be made. Great as this challenge appears, its solution is further constrained (Fig. 2) by practical bounds imposed on the inspection by design, manufacturing, materials, and the field environment. It is clear that a competent and broadly trained engineer will be essential if satisfactory solutions are to be found. To illustrate these technologically driven needs, the example of the development of an NDE system for inspecting turbine rotor components of military aircraft engines is reviewed in the next section, with particular emphasis on the interdisciplinary expertise required to develop a solution. Reference is also made to parallel developments in the evaluation of pressure vessels and piping, particularly in the nuclear power industry.

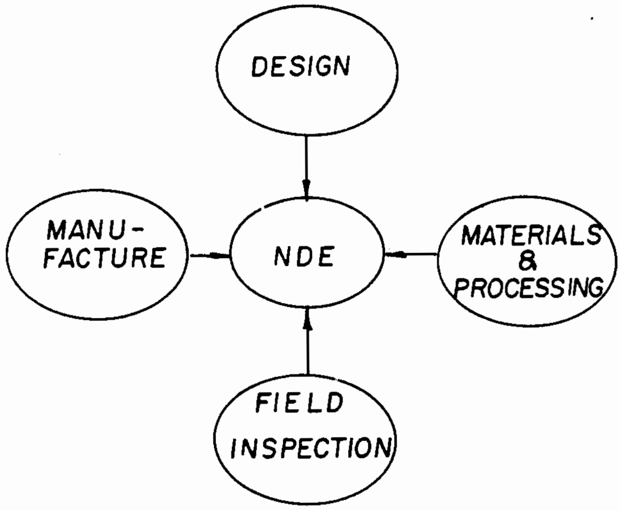


Fig. 2. Interfacial bounds on NDE.

The breadth of these requirements places heavy demands on traditional, disciplinary education and training. New programs are needed to develop personnel at all levels, including researchers developing new techniques, engineers designing structures and defining the NDE procedures for their inspection, and inspectors applying the techniques in the factory or field. A curriculum being developed at Iowa State University to satisfy this need, particularly at the B.S. and M.S. engineering levels, is described in the final section. This takes the form of an existing, accredited curriculum, with a specialty in NDE obtained by selecting elective courses which cover the aforementioned interdisciplinary topics.

INTERDISCIPLINARY ELEMENTS OF RECENT TECHNOLOGICAL ADVANCES

The example of the Retirement-for-Cause maintenance philosophy, being developed by the U.S. Air Force for jet engine components, is illustrated in Fig. 3 (4, 5). Today, all parts which reach their design life are removed from service, irrespective of their individual condition. However, in accordance with safe life design procedures, only 0.1% of these would be expected to have a macroscopic, detectable flaw. If an NDE system and suitable methodology were available, for each disk "retired for cause" an additional 999 could be returned to service. Lifetime predictions, shown at the bottom of the figure, indicate that after 10 design lifetimes over 800 of the original disks would remain, after 25 lifetimes over 500 would remain, etc. The cost savings could be immense. Over $250 M has been estimated for the F100 engine alone (5).

Figures 4-7 summarize some of the concepts which are the basis for this approach. The majority of the fatigue life of a turbine disk is spent in the crack initiation period, Fig. 4. Due to the variability in the microstructure of individual components, crack initiation time must be described statistically, with a distribution varying over several orders of magnitude, Fig. 5. In order for retirement for cause to be successful, NDE must be able to reliably achieve an inspection size limit such that the residual life to failure exceeds the time before the next inspection by a suitable safety factor. This factor must be chosen to avoid excess costs due either to failure or to manufacturing of unneeded parts, Fig. 6. Given the existence of the NDE technique, parts will be utilized in accordance with the schedule in Fig. 7. At the beginning of each service interval, it may be assumed that no flaws exist with sizes in excess of the NDE limit. During the interval, a postulated flaw of size just less than this limit would grow to a size given by the open circle, which is less than the critical size by an amount determined by the safety factor. If the part passes the next inspection, the cycle reinitiates and continues periodically until a flaw is found and the part is rejected.

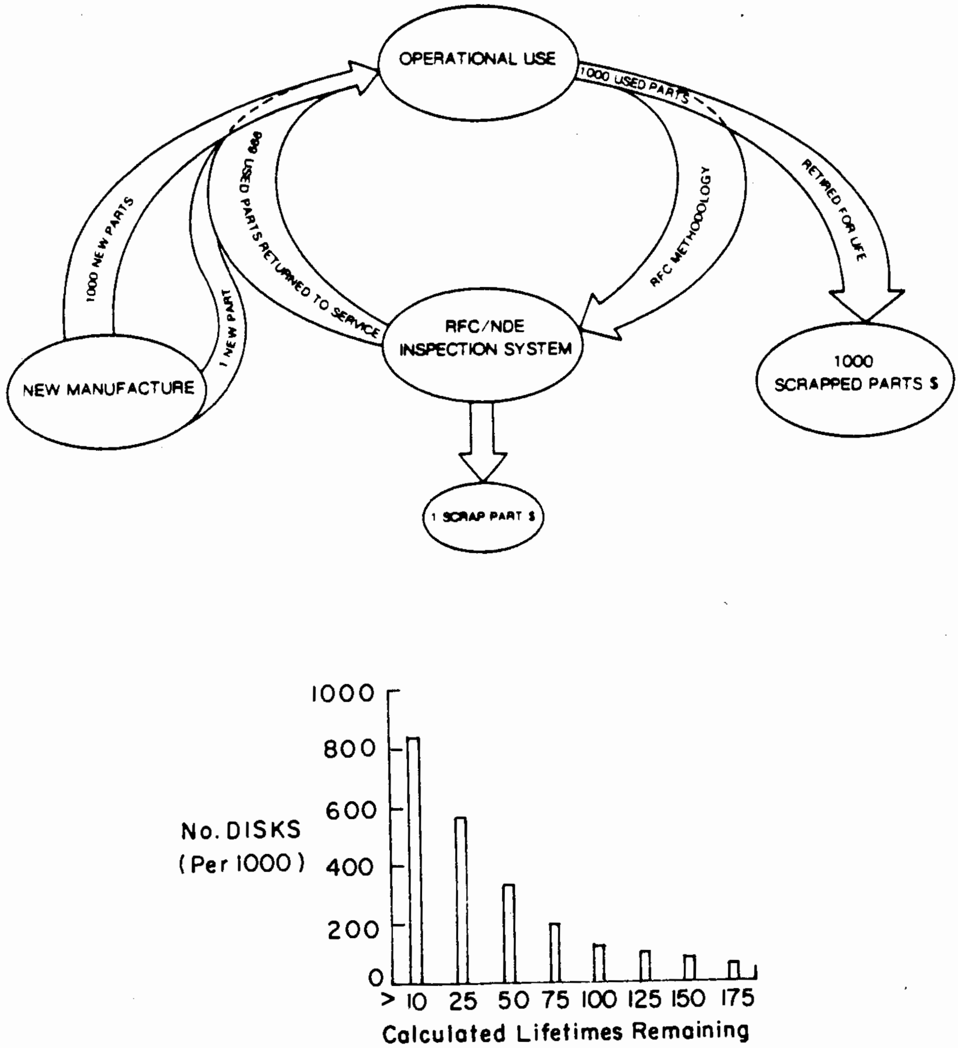


Fig. 3. Retirement-for-cause maintenance philosophy (drawing after Systems Research Laboratory, Dayton, Ohio).

The implementation of such a system raises several technique issues with which today's engineers are grappling. First, all of the problems associated with constructing, installing, and operating an automated system in a maintenance environment are involved. Critical flaw sizes must be determined, and this requires decisions regarding the appropriateness of deterministic versus probabilistic fracture mechanics. Finally, trade-offs must be made in the design of the NDE system. Construction of a system using state-of-the-art NDE techniques can be anticipated to produce a system which will function smoothly, but will not realize all of the potential economic benefits due to higher than desired false acceptance or false rejection errors. Incorporating a more advanced measurement technology promises greater potential payoffs through reduction of these errors, but has greater risk of unreliable operation in the field. Restricting attention to the selection and design of the physical measurement, the first consideration is that the NDE system exhibit a satisfactory reliability in detecting flaws of size greater than the critical size. Typically, such systems are designed on the

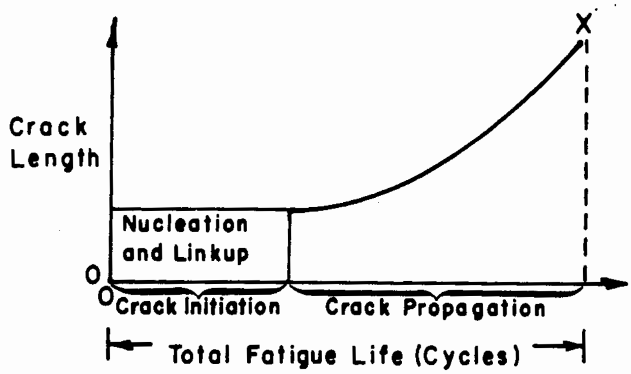


Fig. 4. Total fatigue life segmented into stages of crack development, subcritical growth and final fracture (5).

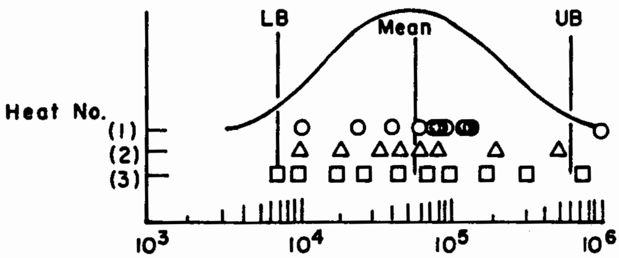


Fig. 5. Material data scatter results in conservative life prediction (5).

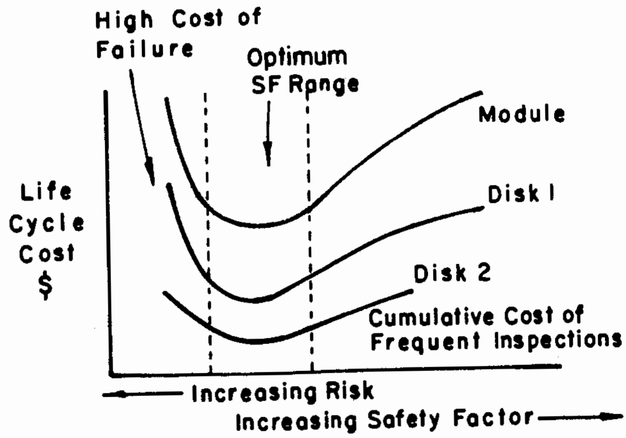


Fig. 6. Safety factor is determined from an economic balance between high cost of failure versus cumulative costs of frequent inspection (5).

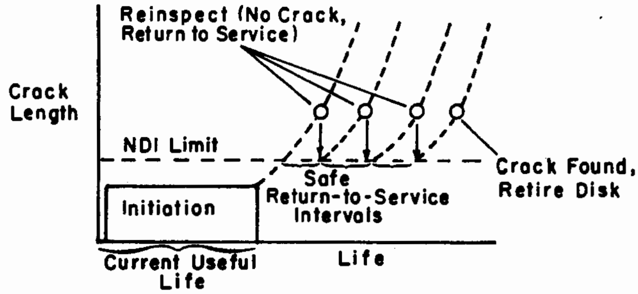


Fig. 7. Basic retirement-for-cause concept (5).

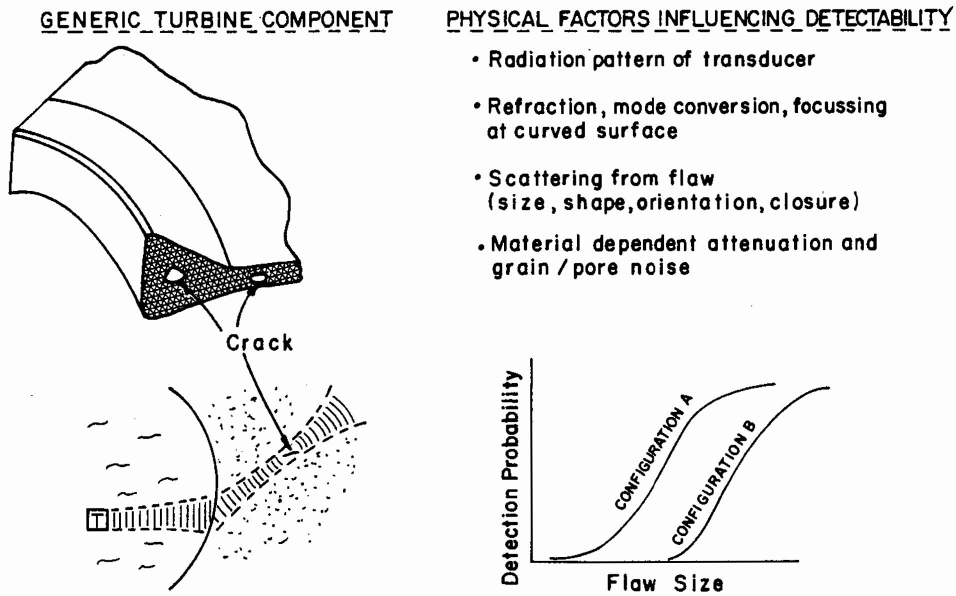
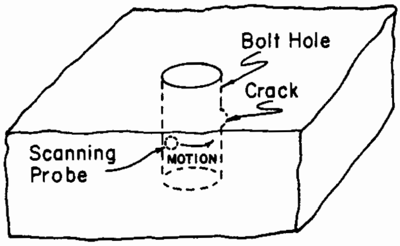


Fig. 8. Elements of models for ultrasonic flaw detectability in turbine rotor bores.

basis of experience. Naturally, opinions can differ, particularly when new flaw or part geometries are encountered. Tools for predicting detection reliabilities are presently under development. Figures 8 and 9 summarize these for the cases of ultrasonic (6-9) and eddy current inspection (10-12). In each case, models of the energy-flaw interaction, of the measurement process, and of the noise sources are combined to predict the signal-to-noise of the measurement. Various candidate configurations can then be compared to see which has the higher probability of detecting the expected flaws. For the case of eddy currents, a variety of candidate probes is available, and the process includes the definition of figures of merit which allow the probes to be intercompared. First generation detection models are now available which directly predict the probability of detection for both the ultrasonic (9) and eddy current (12) cases for turbine component geometries. Experimental evaluation and model refinement are in process.

Given the design of a system to detect critical flaws with sufficient reliability, it is essential to avoid excess false rejection of good parts due to the detection of subcritical defects. Hence, classification and/or sizing algorithms are needed to provide additional information regarding questionable parts.

CRACKS IN BOLTHOLES



CANDIDATE PROBES

- SIMPLE COIL
- FERRITE CORE COIL
- TAPE RECORDING HEAD
- YIG RESONATOR
- MICROWAVE PROBES
- DUAL, ORTHOGONAL PROBES (ECP)

FIGURE OF MERIT

- $S_N \triangleq \dfrac{\text{Peak Signal (Flaw)}}{\text{rms Noise}}$
- $S_C \triangleq \dfrac{\text{Peak Signal (Flaw)}}{\text{rms Clutter}}$
- $D \triangleq \dfrac{\text{Peak Signal (Flaw)}}{\text{Peak Signal (Lift-off)}}$

RECIPROCITY RELATION

$$\Delta Z = \frac{1}{I^2} \int_{S_F} \left\{ (\hat{n} \times \tilde{e}) \cdot h' - (\hat{n} \times \tilde{e}') \cdot h \right\} dS$$

Z = Coil Impedance

e, h = electric, magnetic field

I = electric current

S_F = flaw surface

$' \Rightarrow$ flaw present

Fig. 9. Elements of models for eddy current flaw detectability in bolt holes.

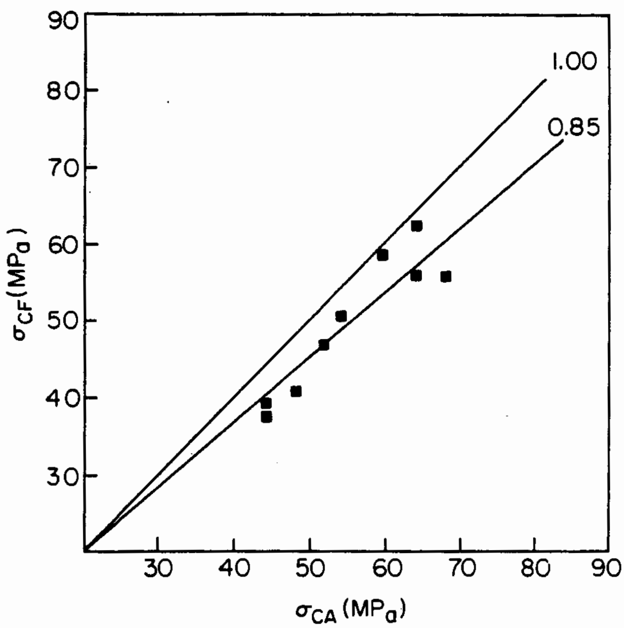


Fig. 10. Acoustically predicted, σ_{CA}, versus destructively measured, σ_{CF}, failure stress of surface cracks in pyrex glass (14).

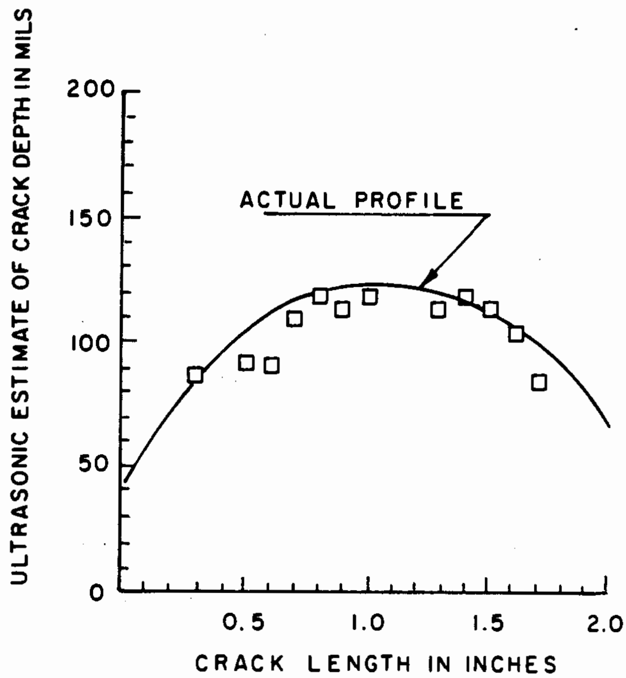


Fig. 11. Sizing of fatigue crack using signals diffracted from crack tip. Actual profile is compared with profile obtained with 2.25 MHz shear waves (16).

Examples of candidate ultrasonic techniques to size cracks and inclusions are illustrated in Figs. 10-11. When wavelengths are large with respect to the size of a crack, a comparison of the elastic wave scattering theories and the deformation of the crack under static load have shown that a direct link exists between the absolute amplitude of the scattered fields and the maximum reduced stress intensity factor of the crack (13). Experiments have borne out this relationship, as illustrated in Fig. 10 (14). Here the failure stresses predicted from long wavelength Rayleigh wave scattering, σ_{cA}, are compared to those determined destructively, σ_{cF} for measurements on glass. The agreement is excellent.

At the other extreme, when wavelengths are short with respect to the crack size, the wave-flaw interaction is dominated by scattering from flash points on the crack edges (15, 16). From measurements of the relative times of these signals, or their interference in the frequency domain, the flaw size can be estimated. Figure 11 presents the results of sizing fatigue cracks in the bore of an electricity generating turbine using this technique (16).

Inclusions, as well as cracks, must be characterized, particularly in disks made by powder metallurgical techniques. Table I presents the results of sizing a naturally occurring, needle-shaped ceramic inclusion in a nickel-based superalloy turbine disk (17). In this case, focused beam imaging was used to determine the length of the inclusion, and the inverse Born sizing algorithm (18), based on the detailed time history of the backscattered signal, was used to determine the small, transverse dimensions. A very favorable comparison to the actual dimensions of the flaw, as determined by destructive sectioning, was obtained. The ability to measure the small dimensions of the inclusion was essential to correctly identify its needle-like shape.

Table I. Comparison of nondestructive and metallographic examination results for ceramic inclusion in nickel-based superalloy.

	Rockwell International Science Center Test Bed	Rolls-Royce Sectioning	
	Flaw (in.)	Flaw (in.)	Reaction Zone (in.)
X Axis	0.172	0.161	0.178
Y Axis	0.007	0.011	0.036
Z Axis	0.006	0.002	0.009
	Angle 4.3°	4° - 6°	

Acoustic impedance higher than the surrounding metal is consistent with a ceramic inclusion.

The designers of the RFC system are presently faced with the evaluation of these and other alternative techniques for ultrasonic and eddy current inspection. Knowledge of a wide range of disciplines is obviously required.

These problems are shared by all industries. Table II summarizes specific examples in the nuclear industry. Ultrasonics is used extensively in the inspection of welds in both the pressure vessel and its piping, as in the inspection of turbines. Electromagnetic techniques are being used to evaluate steam generator components, and acoustic emission is used for monitoring the integrity of the pressure vessel, including leak detection.

Table II. Nondestructive evaluation problems in the nuclear industry.

I. Ultrasonics

A. Welds
1. Pressure vessels
   a. ASME Section XI
   b. PISC I
   c. PISC II
   d. British DDT
2. Piping
   a. austenitic steel material effects
   b. intergranular stress corrosion cracking

B. Turbines

II. Electromagnetics

A. Steam generator tubing

III. Acoustic Emission

A. Pressure vessels

Also shown in the table are some of the areas of present difficulty. In the U.S., Section XI of the ASME Pressure Vessel and Boiler Code (19) specifies the required inspection. However, a series of round robin tests sponsored in the U.S. by the Pressure Vessel Research Committee (PVRC) and in Europe by the Plate Inspection Steering Committee (PISC) have raised questions regarding the reliability of these procedures (20). Techniques derived from recent research advances

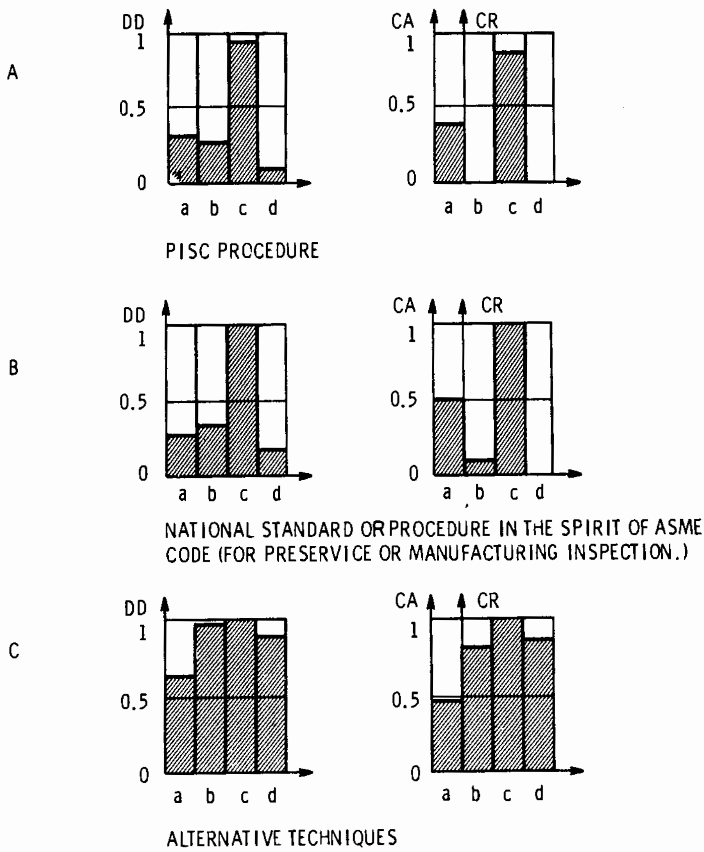


Fig. 12. Average cumulative diagrams of defect detection (DD) and Correct Rejection or Acceptance [CR(CA)] as a function of defect category. These are (a) small acceptable defect, (b) small rejectable defect, (c) large continuous defect, and (d) composite (multiple type) defects (20).

have been shown to produce much more satisfactory results, as illustrated in Fig. 12 and re-established in the recent British Defect Detection Trials (21). Again, the engineer must select from the candidate techniques the one suitable to the application at hand.

In piping welds, another source of difficulty is dominant. Here material effects contribute heavily to the inspection problem. Anisotropic sound velocities, produced by columnar, oriented grains in austenitic weldments (22), introduce mode conversion and refraction which complicate the inspection. Cracks can have a multiple and irregularly branched shape, due to intergranular stress-corrosion cracking, whose scattering properties are hard to predict (23). The engineer must carefully consider these material effects in defining the test procedure.

A MODEL CURRICULUM

Figure 13 summarizes the interdisciplinary knowledge that the NDE engineer should have at his disposal in order to deal with such problems. Consider the steps required to make an accept-reject decision, Fig. 1. In order to be able to assess the material condition through nondestructive measurements, the engineer should have a working knowledge of such subjects as elastic wave theory, electromagnetic wave theory, imaging and inverse scattering, statistical estimation, r.f.

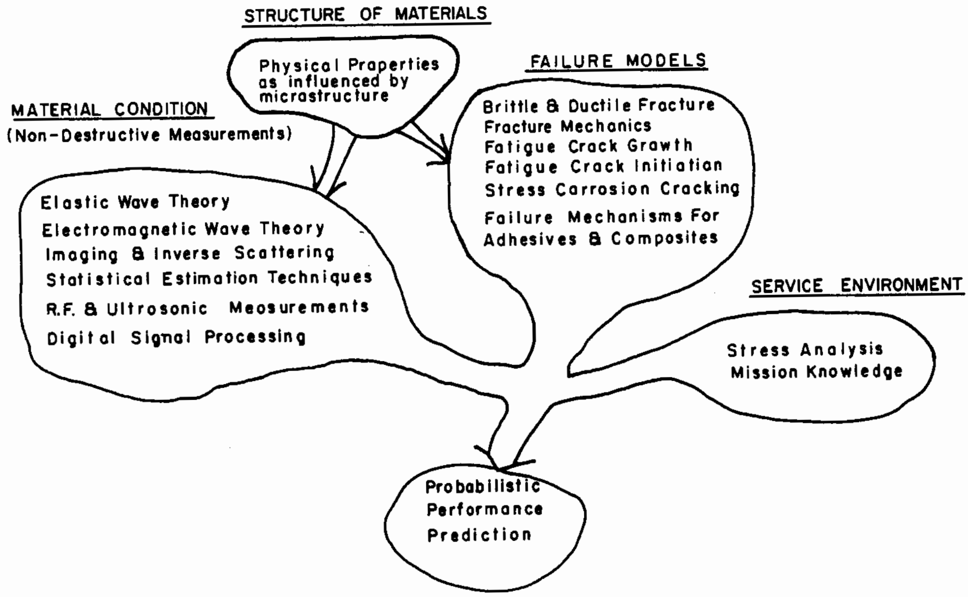


Fig. 13. Interdisciplinary knowledge required by an NDE engineer.

and ultrasonic measurements, and signal processing. The nondestructive measurement results must be coupled with knowledge of failure models, depending on the details of the microstructure, and the effects of the service environment to allow a probabilistic estimate of the part performance to be made. However, the measurement cannot be correctly interpreted without an understanding of the physical properties and characteristics of the material, as determined again by its microstructure.

In response to this need, an NDE curriculum is being developed by the Department of Engineering Science and Applied Mechanics at Iowa State University. The basic philosophy is to provide a B.S. or M.S. engineering degree with a specialty in NDE. This is based on an existing, accredited curriculum, combined with selected new offerings. As described by Weiss (24), the existing curriculum contains many of the necessary elements shown in Fig. 13. In addition to several courses covering failure modeling and material behavior, this includes an undergraduate course and laboratory on the Principles of Nondestructive Testing. Also, a graduate seminar on Advanced NDE Concepts is available. New graduate courses in the developmental stages include EM5XX, Ultrasonic and Electromagnetic Nondestructive Measurement Principles, and EM6XX, Probabilistic Accept/Reject Decisions. As an example, Table III contains an outline of the former course.

Table III. EM5XX: Ultrasonic and electromagnetic nondestructive measurement principles.

I. ELECTROMAGNETIC TECHNIQUES FOR FLAW DETECTION AND SIZING

- A. Qualitative Summary of Available Techniques
  1. Nonmagnetic materials
     - a. potential drop
     - b. current perturbation
     - c. eddy current
     - d. microwave
  2. Magnetic materials
     - a. flux leakage
     - b. magnetic particle

B. Electromagnetic Field Theory
   1. Maxwell's equations
   2. Constitutive relations/ferromagnetism
   3. Solution to wave equation
      a. free space/quasi-static
      b. metals/skin effect
      c. metals/pulsed regime
      d. microwaves/radiation effects
   4. Fields produced by practically important probes
      a. straight-wire
      b. loop
      c. YIG sphere
      d. microwaves
   5. Flaw scattering models
      a. perturbation
      b. finite element

C. Examples of Practical Configurations
   1. Tube inspection
      a. single frequency
      b. multi-frequency
   2. Bolt hole inspection
      a. pancake coil
      b. complex coil

II. ULTRASONIC TECHNIQUES FOR FLAW DETECTION AND SIZING

A. Qualitative Summary of Available Techniques
   1. Pulse-echo
      a. A-scan
      b. B-scan
      c. C-scan
   2. Pitch-catch
   3. Through transmission

B. Ultrasonic Wave Theory
   1. Concepts of stress/strain/elastic constraints
   2. Elastic wave equation
   3. Solutions to the wave equation
      a. plane waves
      b. reflection and transmission at interfaces
      c. Rayleigh waves
      d. plate waves
      e. finite beams/diffraction
   4. Transducers and models
      a. piezoelectric
      b. electromagnetic
      c. capacitive
   5. Flaw scattering models
      a. long wavelength/quasi-static
      b. intermediate wavelength
      c. short wavelength
   6. Data interpretation techniques/inversion
      a. long wavelength
      b. resonance
      c. spectroscopy
      d. model based reconstruction
      e. imaging

C. Practical Systems
   1. Near net inspection of turbine disk
   2. ASME code inspection of pressure vessel welds
   3. Inspection of railroad rail
   4. Inspection of aircraft wing lap joints

III. MEASUREMENTS OF MATERIALS PROPERTIES

A. Stress Detection
   1. Magnetic
   2. Ultrasonics

B. Nodularity Measurement/Ultrasonic

C. Hardness Measurement
   1. Eddy current
   2. Ultrasonic

It is believed by the author and his associates at Iowa State University that the continued development of curricula such as the above will be required at a number of major universities if an even more serious shortage of NDE engineers is to be avoided in the future.

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DISCUSSION

Q: You have to attract students into a program before you can produce the product that you are looking for. We've had good experience in another field by having a clearly-identified option within a discipline and actually a menu of several options where each one is related to some application, and I think this is one way to attract students. How do you see that this can be done in this case? What kind of application would you relate to it? Specifically to the aerospace industry and to some particular project within it? How can you make this come alive for engineers who, by and large, I think, tend to become interested in something, even very abstract, when they can relate it to a need, because NDE is, after all, a tool.

A: I think we have a lot to learn in that area. I certainly do since I have been with an industrial organization until just a couple of years ago. One way in which students are now attracted is through the research programs. In particular, we're beginning to have undergraduate students who work in the summer on the research programs. These research programs are obviously focused on particular technical problems which you're addressing for those particular customers. I think that's an effective mechanism to spread things by word of mouth.

An additional experience that has been had at Iowa State has involved the survey course that has been taught for several years. The students who have taken that course have found it very easy to get jobs and they seem to have viewed that as an asset in their "educational portfolio." That may be the most effective mechanism. The student also finds that there is a class of problems which he doesn't know everything about, and I think industry may like that. That also seems to be an asset. (Response by R.B. Thompson, Ames Laboratory, Iowa State University.)

A: I agree entirely that there has to be a menu that the student can choose from, particularly in a broad-based program such as an engineering science program. We have, in fact, listed a number of different options that the students can take by selecting particular sets of electives within the basic program. The one that I illustrated here in NDE is one of about half a dozen different options that we make available to the students. In terms of attracting students, as I indicated and I'm sure it's true elsewhere, we do have a very active, on-going research program. What is extremely pertinent to the point of this meeting today is that most of these are funded by government agencies. We see a lack of funding by industry people and a lack of industrial involvement in developing problems that faculty members can work on and which would thereby attract students to work in these particular areas. There's certainly nothing wrong with the research programs being funded by the federal agencies, but I think they tend to be broader in scope than the sort of problems that industry wants to address itself to. (Response by H.J. Weiss, Iowa State University).

A: Indeed, industry does have problems and one of the problems in teaming with a university is that industrial research is, for the most part, proprietary. This means that you can't publish, which means that you die at the university. So we have a dichotomy which at Martin Marietta in Denver we are attempting to address and to solve. The technical problems are there. There are funds. But those tend to be spent where the information is kept proprietary within our own company. I certainly agree with your bottom line, Bill Sproat, that we need to teach an engineer to go out and think and pursue and continue to learn. (Response by W.D. Rummel, Martin Marietta Aerospace).

Q: With respect to academia, when I talk to many professors and ask them what their purpose is, their response is that they are to proliferate and to continue academia. But I see a lot of that happening and I think that if you try to take an NDE program and integrate it into an existing discipline, you may find that you have a lot of problems. The question is, if NDE can be a discipline, can there be a curriculum for it? I think it's a fundamental question that's going to have to be answered, because I hear that, yes, it's a practiced discipline and yet it is not a recognized discipline because it crosses so many boundaries. If it's interdisciplinary, as I've heard from the survey of Prof. Weiss, then you're going to have to combine a lot of these particular courses, especially in electromagnetics.

Texas A&M is utilizing parts of existent courses from its physics and EE departments to form new courses that would be more dedicated, more pertinent, to the NDE-type activity that's going to be conducted. I believe NDE curricula will evolve that way.

But the question is, can it be a discipline? I believe that it can be, but I hear that it can't be, also. I think you're dodging the question. Industry offers jobs in NDE; I don't think you can refute that. There's obviously a need there somewhere.

A: I'm thankful for this chance for a friendly argument. Of course what defines a body of knowledge and practice as a discipline may change from time to time. We use the word "interdisciplinary" today and what we are talking about is crossing, in a certain sense, artificial barriers which have been erected by men. They can just as easily be destroyed by men. To say that 10 years from now NDE will not be a discipline is an incorrect statement. I think what we can say right now is that there are areas of professional interest no one of which constitutes the core for NDE, as perceived by industry or even as perceived by those of us in the university, and it is in that sense that we have to proceed in terms of an "interdisciplinary" program. This does not mean that NDE is not a discipline or could not be defined as a discipline. It is currently not defined as a discipline, but in the process over the years it may eventually become a discipline.

There are a lot of technical details involved in such things as having appropriate accrediting bodies recognize NDE as something for which a curriculum exists. That barrier is not going to be crossed in the near future, as those of us in the university recognize. I really see nothing wrong with developing coursework which draws on people from a number of different areas, a number of different interests, as long as they have the common interest of NDE. (Response by H.J. Weiss, Iowa State University)

Q: When you study the history of medicine, you learn that when the x-ray was developed it was decided to have a specialized field called radiology. If ASNT is bold enough to claim that the people it trains will be on a comparable level of the radiologist, you're all going to be millionaires because you are working on products that cost more than millions of dollars. These are very expensive things you're working on and the economic impact is tremendous, so what I'm trying to say is that whether it's going to be a discipline or not depends on the professional people. I believe strongly that it could be done.

A: I feel that more needs to be said about this very fair question of whether or not NDE can be a discipline or a department. As it happens, I had the experience of being a founder of a new department and I know how difficult that is. There are some ingredients that are required that I don't see in NDE at the present time. These have to do with the demand, with the perception of a large segment of the industrial and academic community that there is, indeed, a need, and also a large volume of research support to go into that area so that a department can be launched with a solid foundation and survive through a few years of poor acceptance within the university itself, and then be able to survive long enough to gain that acceptance. It's rather complicated to do this. (Response by M.L. Yeater, Rensselaer Polytechnic Institute)